Compensation of Coil Magnetization Effects in Nb_3Sn Dipole Magnets

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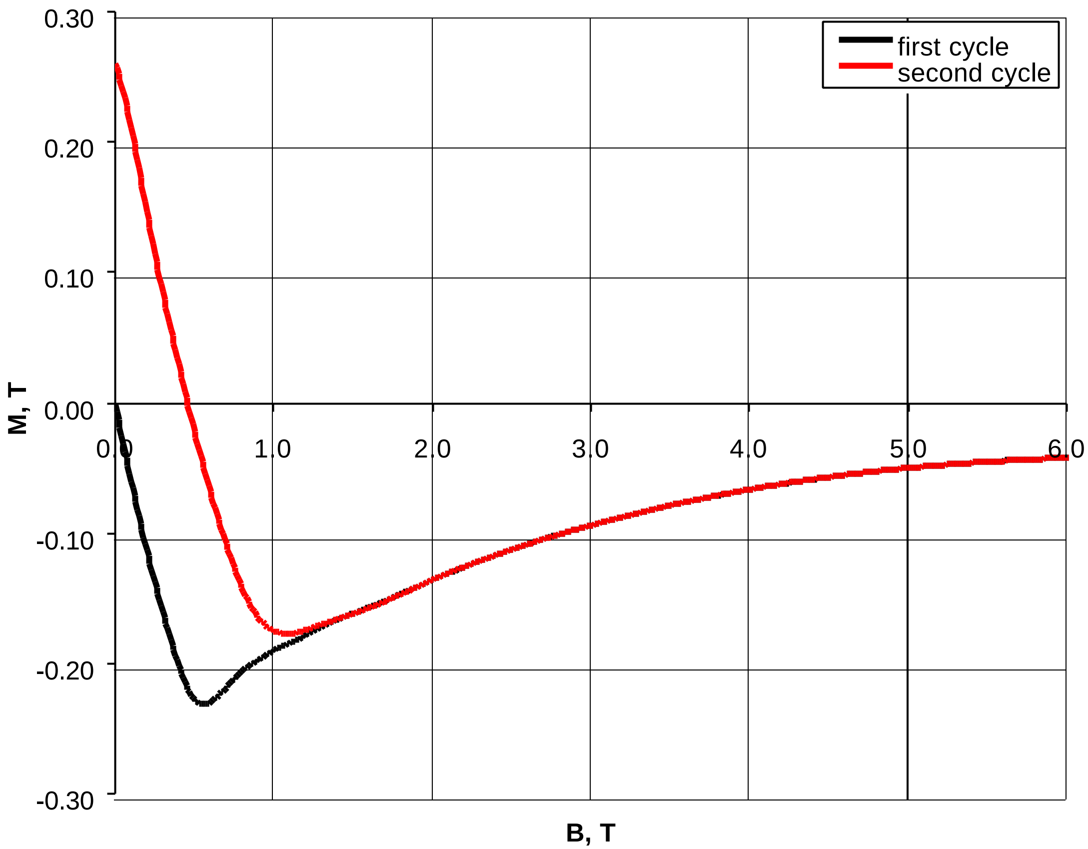
Outlines:

- magnetization Nb_3Sn of strand
- simulation of the persistent current effect
- methods of field sextupole correction
- sensitivity analysis
- magnet dynamic range
- summary

Measured magnetization of Nb_3Sn strands



Magnetization measurements were made on Nb_3Sn strands with J_c(12T)=1600A/mm^2 and D_{eff}=110 mm

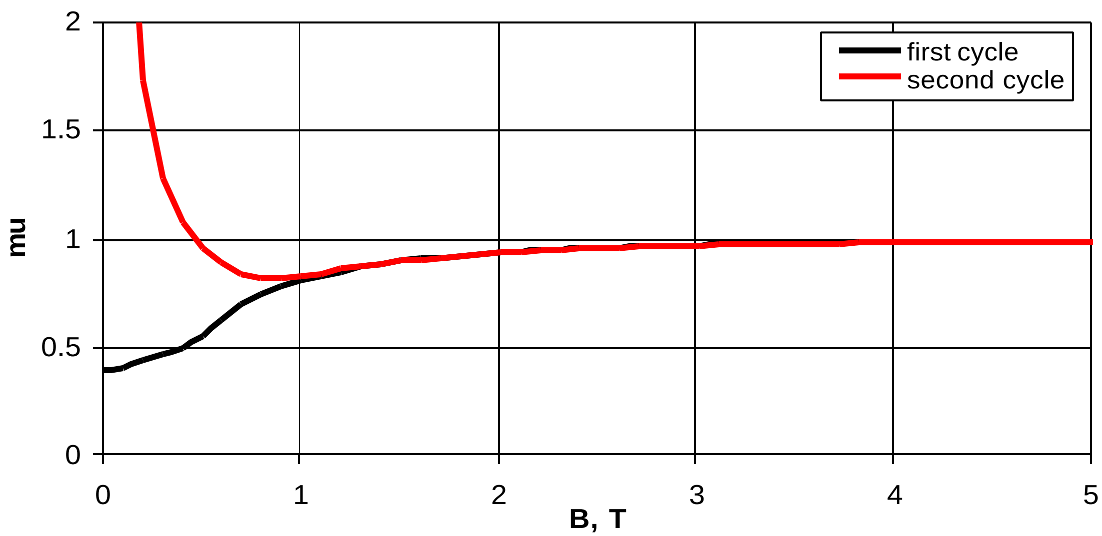
For reference:
NbTi wire with J_c(7T)=1800A/mm^2 and D_{eff}=5mm has $|M|_{max}$ ~20mT

Simulation of persistent currents by finite-element code (OPERA2D)

Magnetic properties of a superconducting material can be expressed in terms of flux density as:

$$B(H) = \mu_0 \cdot H + K_{sc} \cdot M_{sc}(H)$$

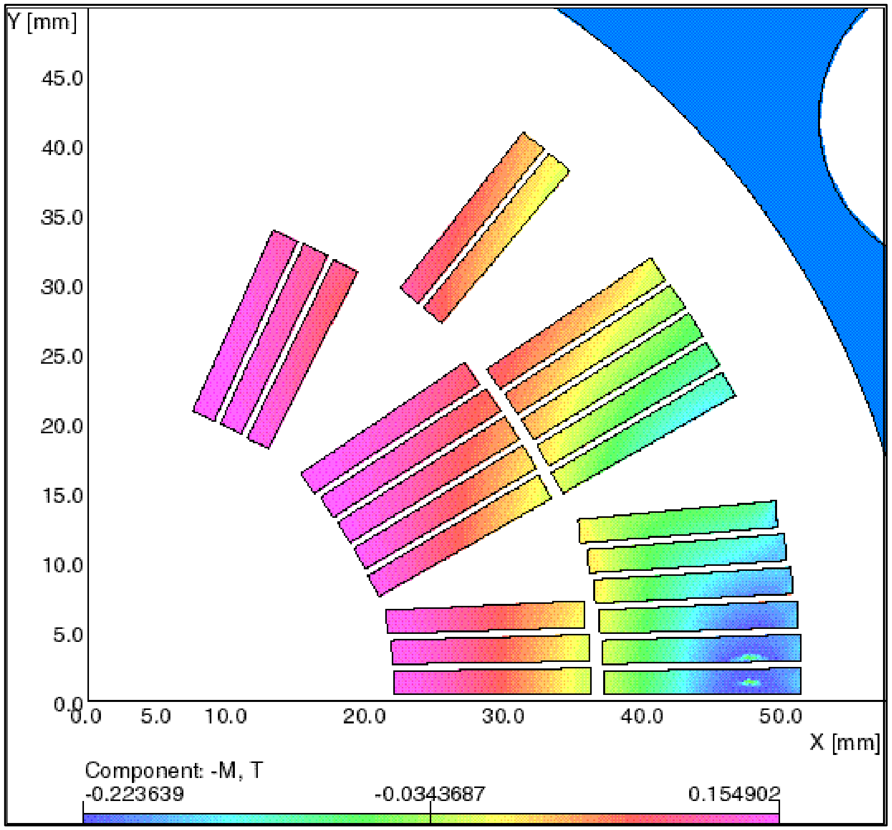
Relative permeability is:



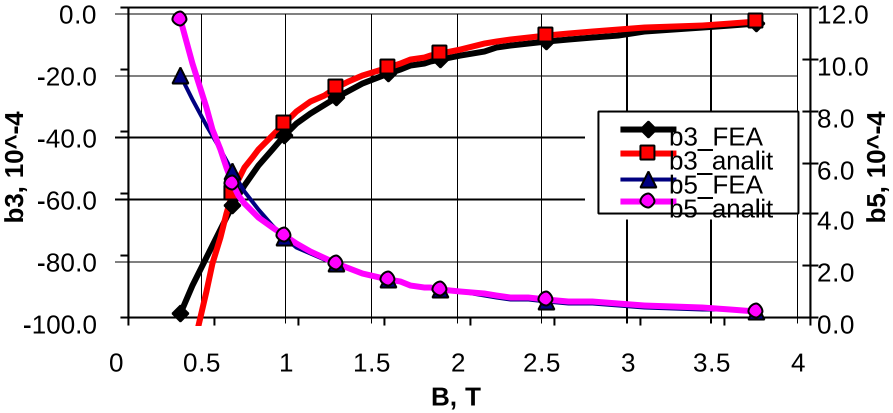
$$\mu(H) = \frac{B(H)}{\mu_0 \cdot H} = 1 + \frac{K_{sc} \cdot M_{sc}(H)}{\mu_0 \cdot H}$$

Verification of the proposed method by comparison with analytical solution

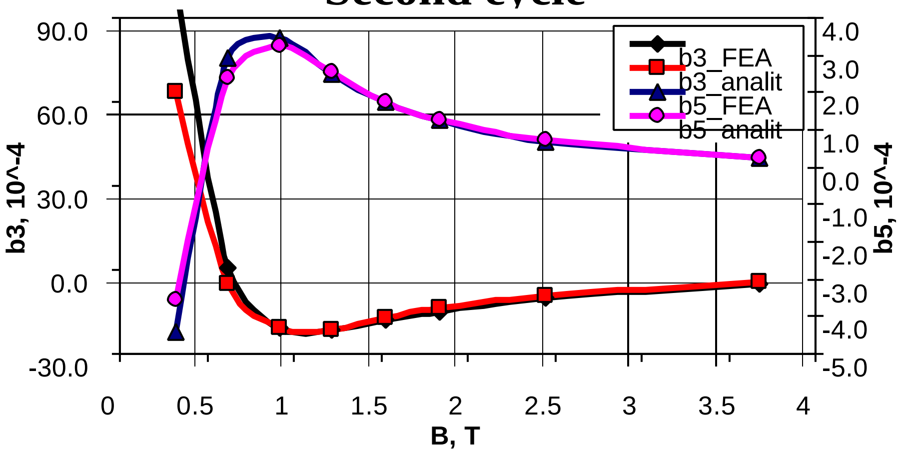
OPERA2D model (second cycle, B_0=1.2T)



First cycle

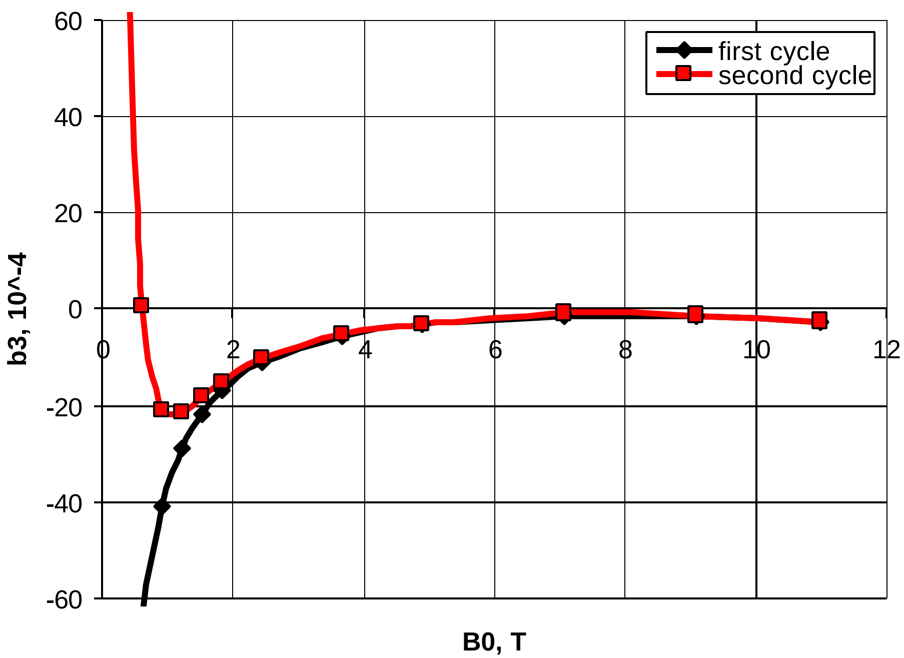


Second cycle

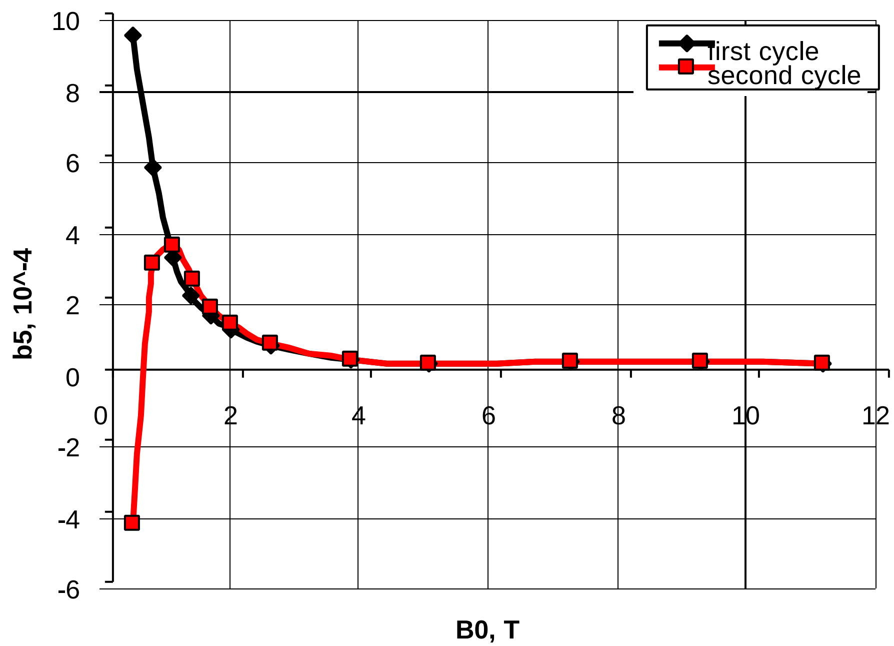


Impact of the coil magnetization effect on the field multipoles

Sextupole component



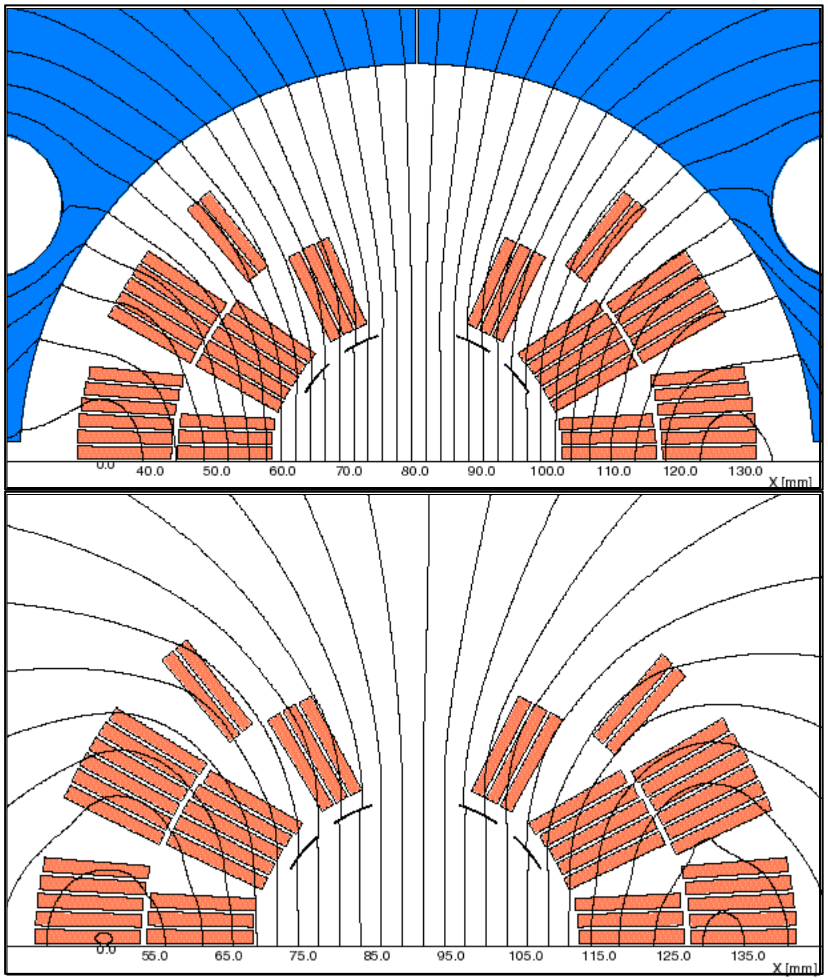
Decapole component



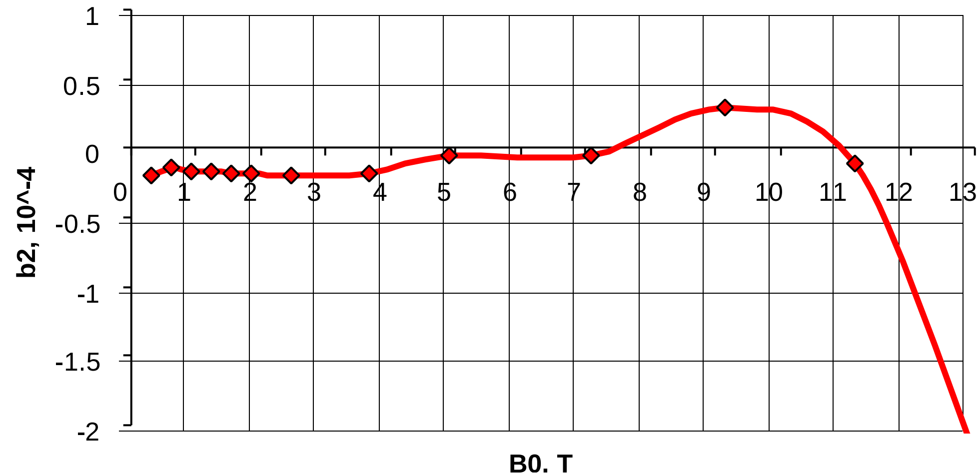
Large negative sextupole component at low fields induced by persistent currents in Nb_3Sn filaments, due to a high critical current density and a big effective filament diameter requires an additional correction

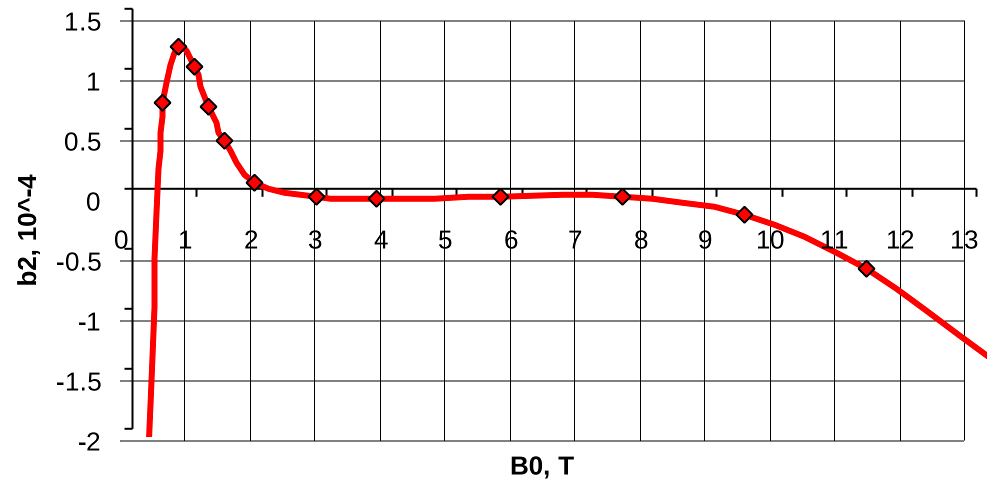
Effect in double bore magnets

“Cold” and “warm” yoke models



Quadrupole deviations vs. bore field





Methods of the coil magnetization effect correction

1. Maximum magnetization of fully penetrated filament:

   $$M_p = \frac{2}{3\pi} J_c D_{eff}$$

   can be reduced only by decreasing D_{eff} that has technological limitations.
2. Active multipoles correction by correcting magnets - always presents and expensive.
3. Passive multipoles correction by superconductor . Required considerable amount of correcting superconducting material that reduces coil efficiency.
4. New developed method of passive correction by ferromagnetic material will be discussed.

Persistent current correction by ferromagnetic material

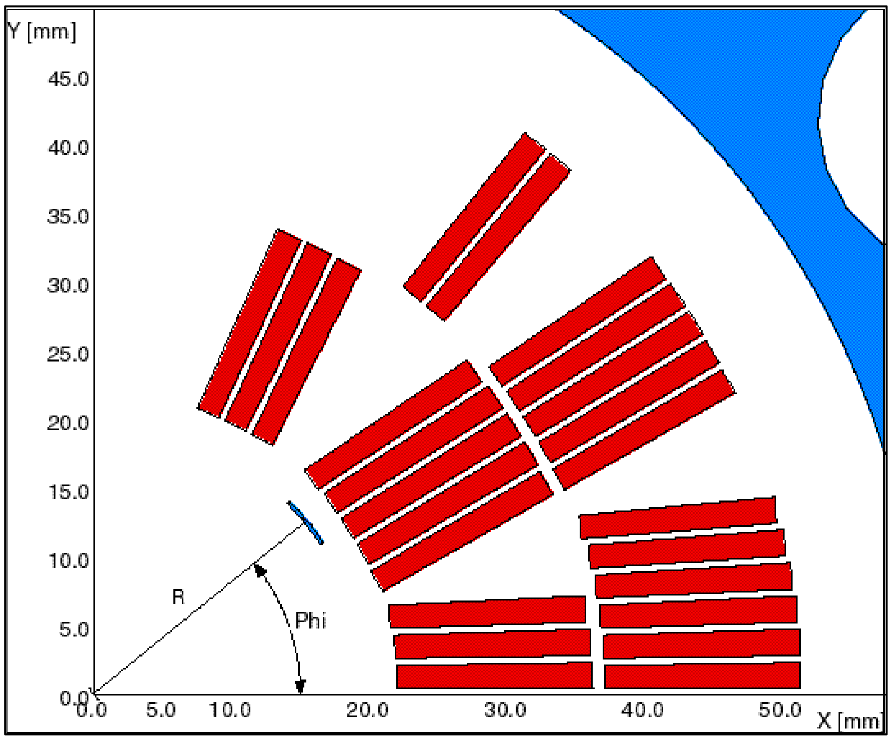
Possible positions of ferromagnetic corrector:

1. **Outside of the coil:**
   - at outer surface of the beam pipe or inner surface of the coil in form of thin iron strips
   - at outer coil surface in form of iron shells (spacers between coil and yoke)

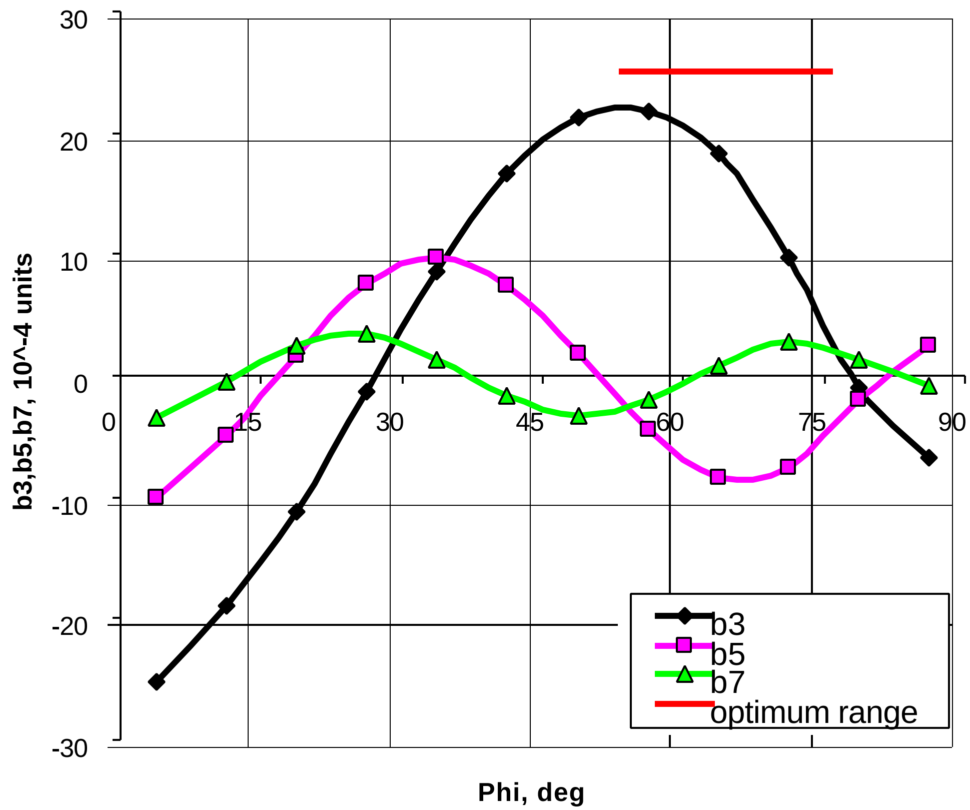
2. **Inside of the coil:**
   - between cables as thin foil strips
   - inside of the cable as a core (instead of SS core)

Optimization of the correcting strip position

OPERA2D model

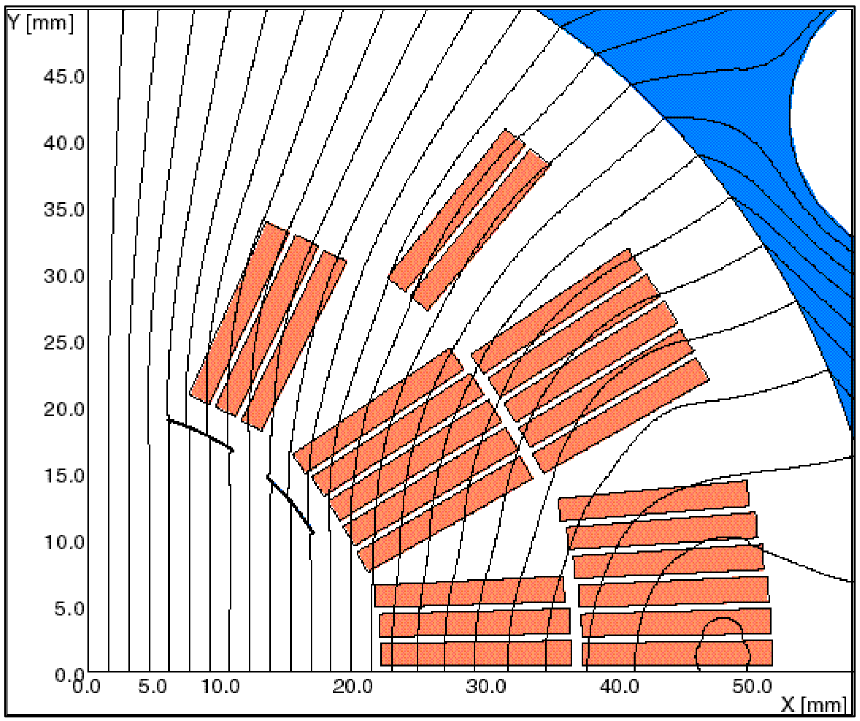


Multipoles vs. correcting shim position (R=19.75mm, Dh=0.2mm, DPhi=7.5deg)

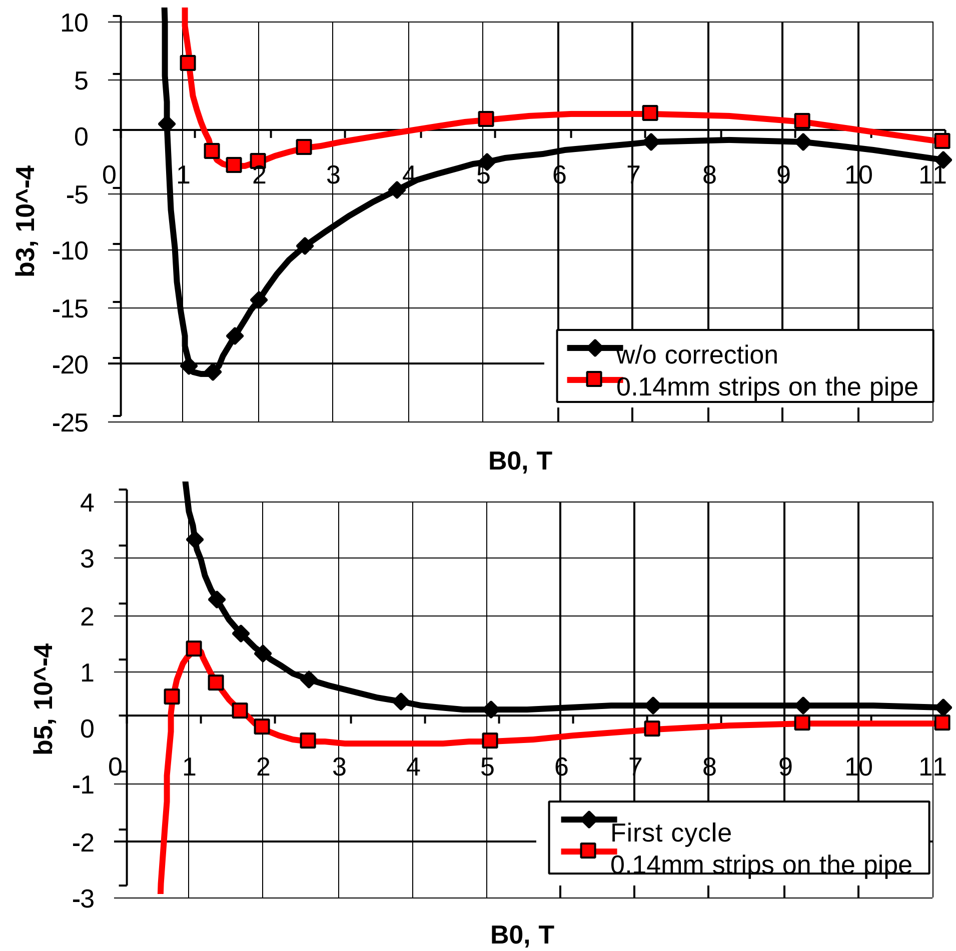


Correction by strips on the beam pipe

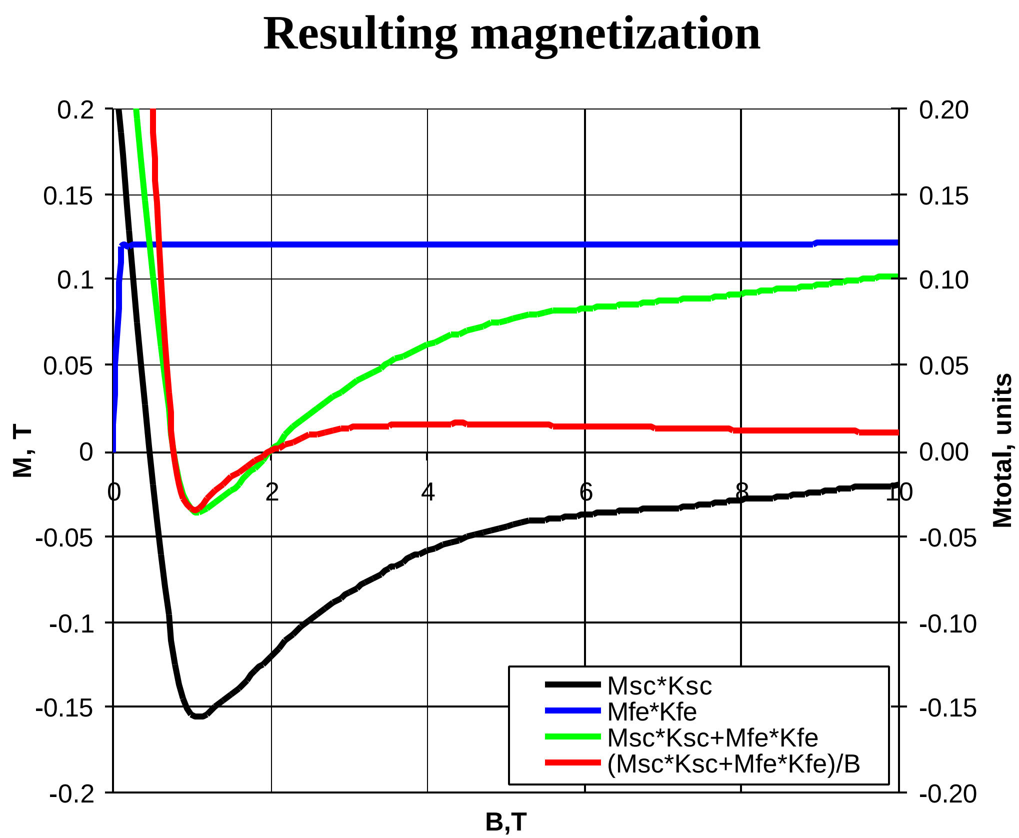
OPERA2D model



Sextupole and decapole vs. bore field



Correction by introduction of ferromagnetic material inside the cable



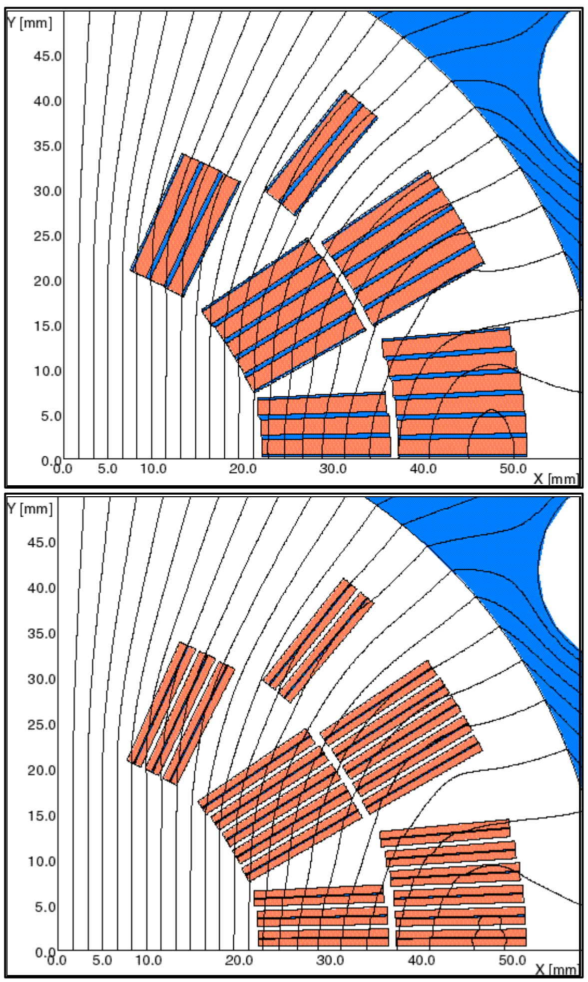
Magnetization of cable with iron core:

$$M(H) = K_{sc} \cdot M_{sc}(H) + K_{fe} \cdot M_{fe}(H)$$

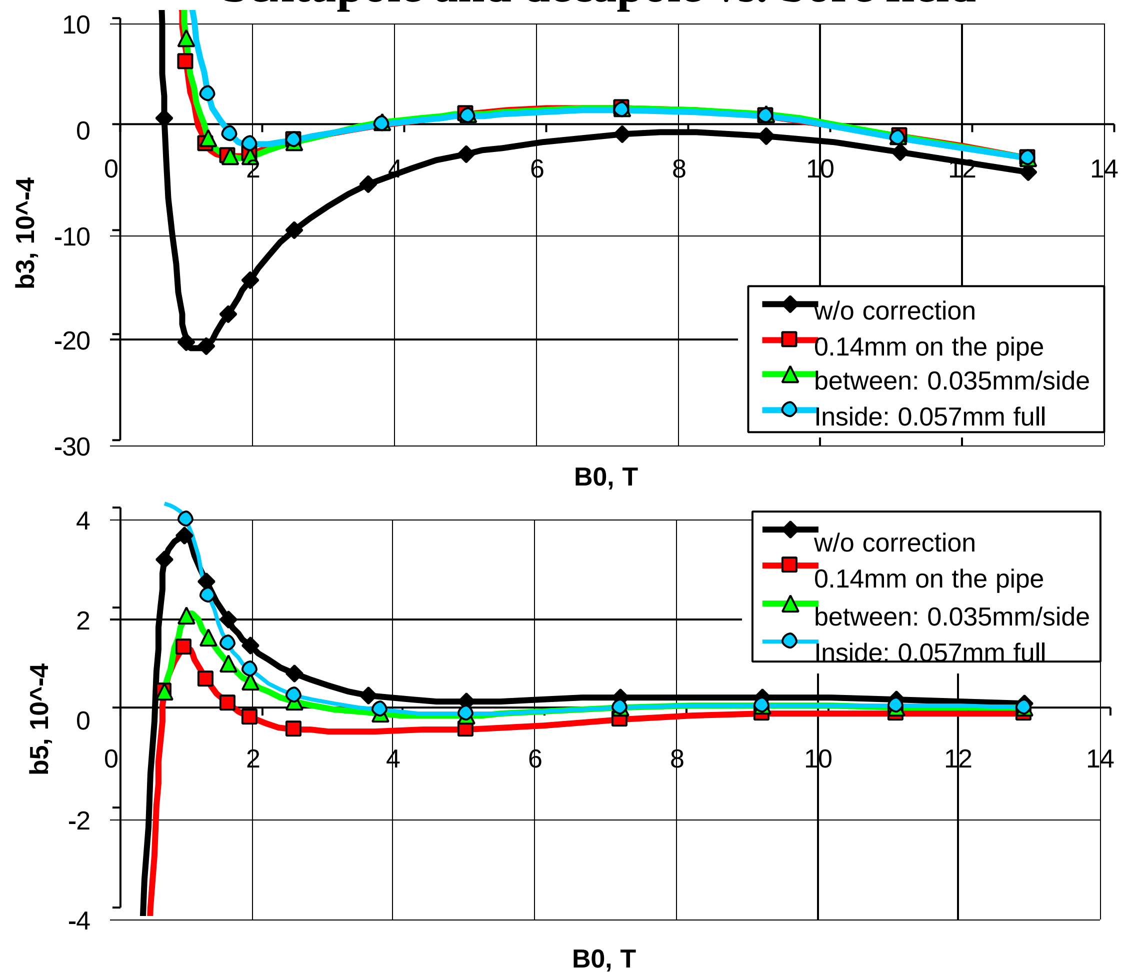
Since superconductor and ferromagnetic have opposite signs of magnetization in the relevant field range - one can find the packing factor of ferromagnetic material, required to cancel coil magnetization

Correcting strips between/inside the cables

OPERA2D models



Sextupole and decapole vs. bore field



Sensitivity analysis

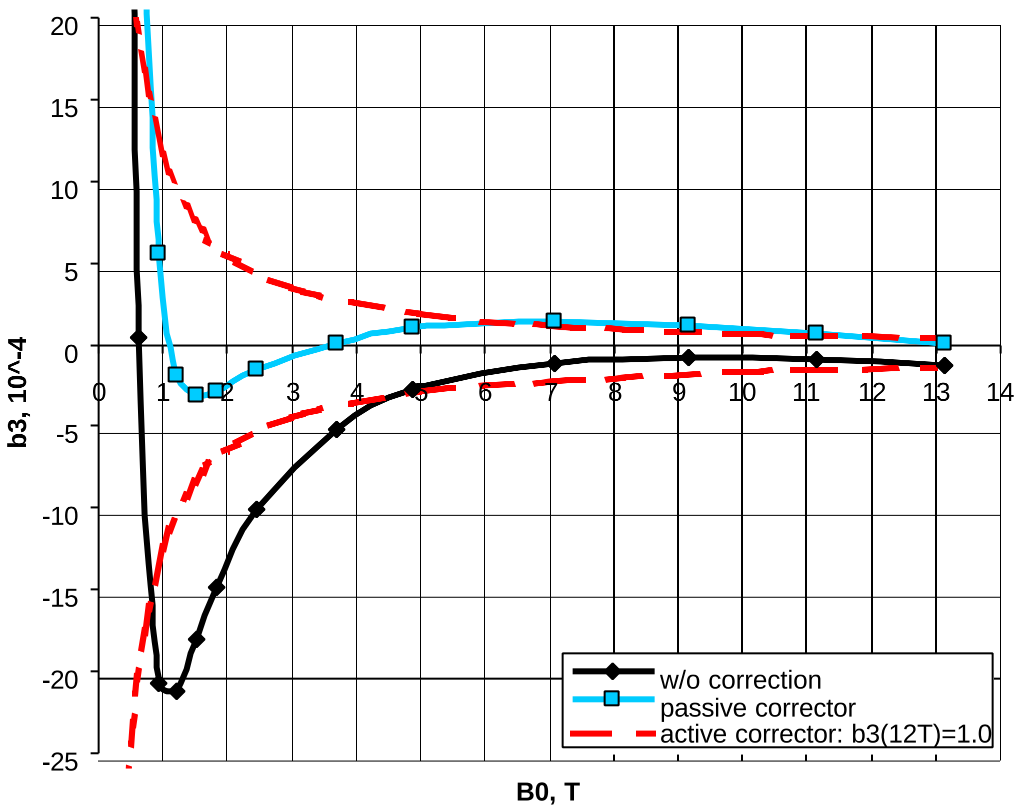
Corrector type	Errors type	Value	Errors in normal multipoles at 1T bore field, units				Errors in skew multipoles at 1T bore field, units				
			Db2	Db3	Db4	Db5	Da1	Da2	Da3	Da4	Da5
Strips on the beam pipe	Pipe horizontal	0.5mm	3.7	0.12	0.66	0.12	0	0	0	0	0
	Pipe vertical	0.5mm	0	0	0	0	0	3.7	0	0.54	0
	Pipe angular	0.5 mm (1.45deg)	0	0.16	0	0.05	0.45	0	3.12	0	0.39
	One strip angular	0.5 mm (1.45deg)	0.25	0.36	0.50	0.10	0.04	0.52	0.48	0.09	0.37
	Material anizotropy	1/0.2	0	0.81	0	1.4	0	0	0	0	0
Strips inside/ between the cables	All strips radial	0.5mm	0	1.0	0	0.7	0	0	0	0	0
	All strips thickness	5mm (10%)	0	2.9	0	0.13	0	0	0	0	0

Required technological tolerances:

- strip position variation < 0.5mm
- strip thickness variation <10%

Achievable magnet dynamic range

Combined sextupole correction



Active corrector strength required to cancel out remaining sextupole:

- **w/o passive correction - 20 units at 1.5T or 2.5 units at 12T;**
- **with passive correction - 1.0 units at 12T (required to cancel the yoke saturation effect)**

Achievable magnet dynamic range with sextupole corrector maximum b_3(12T)=1.0 unit:

- **w/o passive correction - 11T/4T=2.7**
- **with passive correction - 11T/1T=11**
- **with passive correction and SC with J_c(12T)=3000A/mm^2 and D_{eff}=40mm - 12T/0.7T=17**

Summary

1. Persistent current effect in Nb_3Sn magnets is large and requires correction.
2. Proposed method of passive correction with iron strips allows effective reduction of induced sextupole at low fields.
3. Field sensitivity to the corrector misalignment is acceptable for corrector manufacturing and installation tolerances.
4. Combination of passive and active sextupole correcting schemes allows to achieve required magnet dynamic range of 17 at smaller cost for Nb_3Sn strand with $J_c(12T)\sim3000A/mm^2$ and $D_{eff}<40mm$.

References:

1. V.V. Kashikhin, A.V. Zlobin, “Correction of Coil Magnetization Effect in NB3Sn High Field Dipoles Magnets Using Iron Strips”, TD-99-048.
2. V.V. Kashikhin, A.V. Zlobin, “Comparison of Correcting Capability of Passive Correctors Based on a Thin Pipe and Thin Strips”, TD-99-049.
3. V.V. Kashikhin, A.V. Zlobin, “Sensitivity of Field Harmonics in Nb3Sn Dipole Magnet to the Correction Strip Position”, TD-99-068.
4. V.V. Kashikhin, A.V. Zlobin, “Calculation of Coil Magnetization Effect in Superconducting Accelerator Magnets”, TD-00-010.
5. V.V. Kashikhin, A.V. Zlobin, “Compensation of Strand Magnetization in Superconducting Rutherford Cable with Thin Iron Core”, TD-00-011

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